Final Report: “Cross-sensor validation of the Lightning Imaging Sensor”

(NRA 97-MTPE-03; Boccippio, Bateman, Rennó)

20 November 2001

1. Statement of problem

The Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) is the second Low Earth Orbit (LEO) optical total lightning detector, following the Optical Transient Detector (OTD) aboard Microlab-1/OV-1. Both instruments employ a similar design (CCD detector, narrowband filter, frame-to-frame differencing to isolate lighting transients), although LIS was designed with higher sensitivity (and higher resolution due to the lower TRMM orbit). Together, the instruments (when calibrated and validated) provide the first quantitatively defensible measurements of global lightning activity on climatological, annual and seasonal bases.

The LIS was designed with a target 90% lightning flash detection efficiency. The design parameters included a minimum detectable lightning pulse radiance (there being many lightning pulses in a flash). The design mapping from minimum detectable pulse radiance to flash detection efficiency was based on a small sample of high-altitude aircraft (NASA U-2) measurements of the distribution of optical pulse radiances emitted during lightning flashes, and the performance justified prior to launch through a laboratory calibration of the lens/filter/CCD systems. The prelaunch calibration represented a "first cut" in that differences between U2 and OTD/LIS observational geometries, variability in sensitivity across the instrument FOV, and final (on-orbit) threshold settings necessitated by the ambient LEO environment were not considered.

A further complication arises in that the OTD and LIS instruments are designed with an adaptive sensitivity; the detectors are intrinsically less sensitive during daytime (to compensate for brighter daytime background scenes). The instrument performance thus has a significant diurnal variability which must be documented. Further, the environmental (radiation) noise rates rise within the South Atlantic Anomaly (SAA) over southern Brazil, and the data processing algorithms adaptively increase their data rejection rates to compensate. This spatial variability in instrument performance must also be quantified for climatological analyses. A related goal is the quantification of both intrinsic (measurement) and sampling-related variance, so that both maps and error estimates may be computed.

A final complication is that many of the (RF-based) ground detection systems used for direct cross-sensor validation have poorly known or poorly documented performance characteristics, especially unknown range-to-sensor dependencies. Improved understanding of these ground systems is a necessary precursor to satellite validation.

The following are thus desirable goals in validation of the OTD and LIS. Progress has been made on each of the goals, and in some cases, the basic questions have been answered

1. Quantify the performance of ground-based lightning detection systems used for satellite validation.
2. Quantify the sensitivity and intrinsic measurement variance of the OTD and LIS instruments.
3. Quantify the ability of the instruments to detect both cloud-to-ground and intracloud lightning.
4. Quantify the location accuracy of the instruments.
5. Cross-calibrate the instruments to facilitate mission dataset merging.
6. Assess the impacts of sampling on bias, variance and data compositing.
7. Asses the sensitivity of lightning climatologies to algorithmic implementations (specifically, optical pulse-to-flash-to-storm clustering algorithms).

The *generalized benefits* of these results include:

1. Rigorous and defensible calibration of the mission datasets and release of "best possible" climatologies.
2. Determination of modes of variability (temporal and spatial) which are justifiably accessible from the LEO missions.
3. Improved understanding of design parameters, constraints and goals for follow-on geostationary lightning detection missions.
4. Matching of either satellite or ground-based systems with appropriate spatio/temporal domains for specific applications.

2. Summary of Major Accomplishments

2.1 "Executive" Summary

The following represents the best scientific assessment of the PI at the conclusion of this research:

Primary performance characteristics of the OTD and LIS sensors are now known with sufficient accuracy to support an "official" gridded climatology (compiled by the PI and released 9/5/01). A complete performance model of the instruments (more detailed than the prelaunch design and calibration model) is in basic agreement with ground-based validation, with the relative performance of the instruments during day and night, and with the performance of the instruments relative to each other. The residual uncertainty in the calibration (approximately 15%) is now comparable to the intrinsic (instrument-based) measurement variance (also a product of this study), suggesting that ongoing ground validation efforts will be valuable but of diminishing return. Greater emphasis should now be placed on quantifying the sampling-related measurement variance; analytic and statistical methodologies and basic inputs for this effort are also products of this study.

Now that intrinsic measurement variance is known, quantification of sampling-related variance will

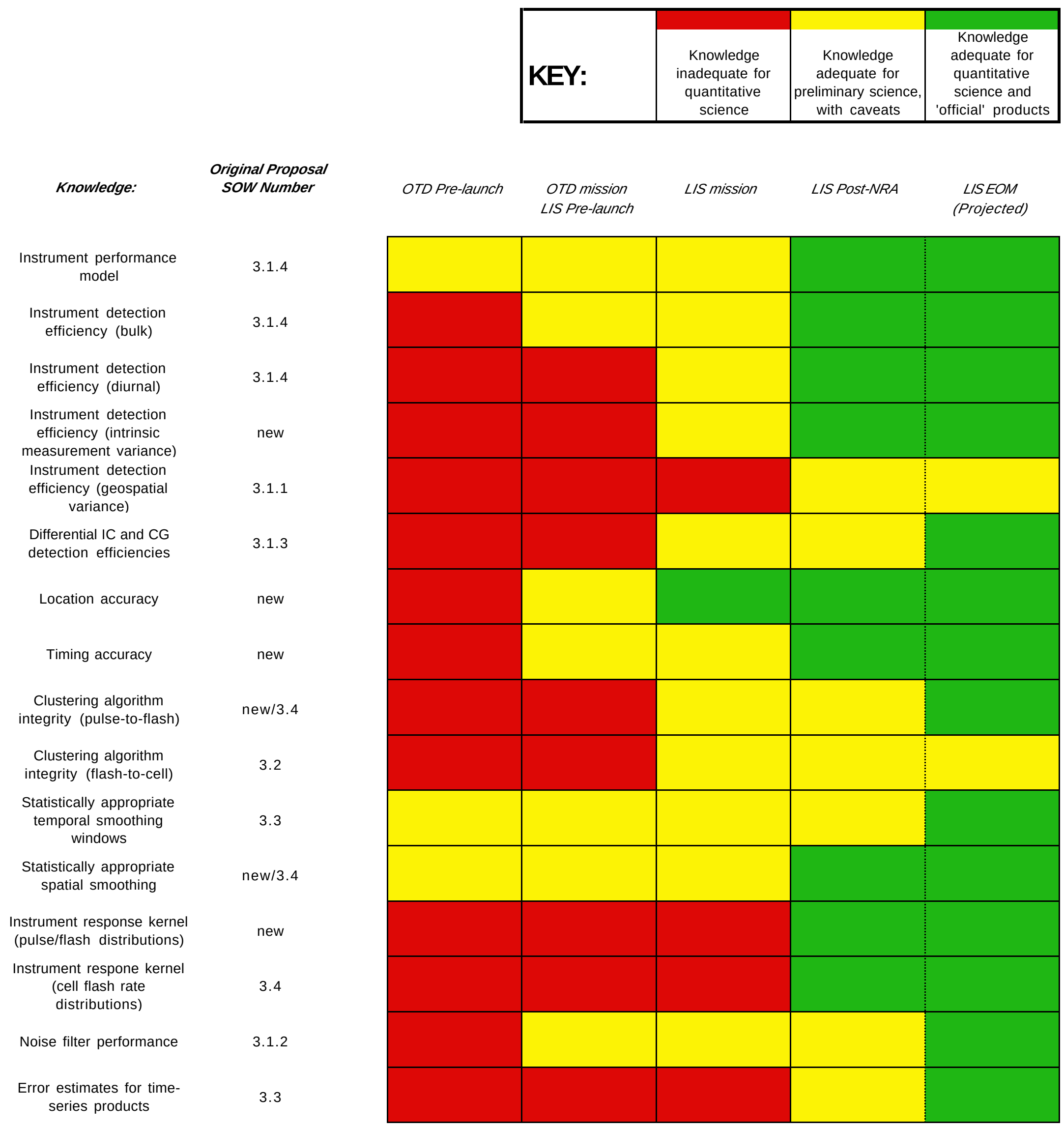


Table 1: PI's assessment of progress in the knowledge of OTD and LIS performance characteristics.

enable release of (justifiable) time series of gridded data at statistically defensible and *appropriate* spatio-temporal resolution. Relase of this dataset is anticipated within the next year.

The calibrated data products currently released include a combined OTD/LIS climatology, a climatological annual (daily) cycle (55-day smoothed), and a climatological diurnal (local hour) cycle. For the combined climatologies, sampling-related variance is negligible (neglecting interannual variability). These climatologies thus now represent significant improvements in the state of knowledge for users such as the atmospheric chemistry community (lightning/NO_x research). The calibrated climatologies provide the data for a mission climatology paper about to be submitted by the LIS P.I. (H.J. Christian) to *J. Geophys. Res.* The cross-calibration and merging of the climatologies enables examination of modes of variability (e.g., spatial mapping of the phase and amplitude of the diurnal cycle) which would be sampling-limited using either mission in isolation.

Table 1 presents the PI's best (and conservative) assessment of the current and projected state of knowledge on LIS performance, before and after the results of this and other LIS validation efforts, including those funded under NRA 97-MTPE-03.

2.2 Concrete Deliverables

The *concrete deliverables* of this study, in approximate order of importance, include:

1. Determination of OTD and LIS intrinsic sensitivity (including diurnal variability), cross-calibration of the mission datasets, and release of the first calibrated, gridded datasets (OTD, LIS, and merged) to the scientific community. This release occurred on 5 September 2001 and was announced to the current LIS/OTD orbit data user community, the AGU Atmospheric Electricity mailing list, and at several recent conferences (IAMAS / Innsbruck, annual TRMM meeting, AMS Satellite conference). The data are available through the Global Hydrology Resource Center; http://thunder.msfc.nasa.gov/data.html. *[Boccippio et al 2002a, 2001b, 2000a, 2000d; Koshak et al 2000, Thomas et al 2000].*
2. Determination of the intrinsic measurement variance of the instruments. This allows quantitative error bars to be placed on individual storm flash rate estimates, and is one of two primary components of variance estimates in climatological time series analyses. *[Boccippio et al 2002a, 2001b, 2001d].*
3. Determination of the range-dependent sensitivity of the NASA/KSC LDAR total lightning detection network and the Global Atmospherics, Inc., long range (offshore domain) lightning detection network. *[Boccippio et al 2000b, 2000c, 2000e, 1999].*
4. Development of a technique for deconvolution of instrument response during estimation of observed lightning parameter distributions, following standard satellite response kernel inversion methodologies. The relevant parameters include the distribution in number of pulses per stroke and strokes per flash (important input parameters for both NASA and SBIR-based efforts to design 2nd-generation CCD detectors), and the distribution of per-cell flash rates (of basic scientific interest in quantifying the spatio-temporal variability in convective regimes). A 'spinoff' result of these techniques is quantification of the cell detection efficiency of the two instruments. *[Boccippio et al 2001b, 2001d].*
5. Development of a statistical (binomially-based) technique to "bootstrap" relative instrument performance estimates. This technique capitalizes on the intrinsic variability in sensor performance across the FOV and with background brightness intensity. *[Boccippio 2001d].*
6. Development of an adaptive gridding technique to produce quantitative 'constant-variance' maps of lightning parameters. Given the conditional nature of lightning occurrence and its very wide (30 dB) dynamic range, these maps should yield superior and quantitatively justifable feature identification, compared with traditional gridding or smoothing techniques. *[Boccippio 2001d].*
7. Demonstration of OTD/LIS intracloud lightning detection capability, and corroboration of incremental data value from IC measurements. *[Boccippio et al 2001a, 2000c, 1999; Thomas et al 2000, Koshak et al 2000, Ushio et al 1999].*

8. Demonstration that OTD and LIS optical pulse-to-flash and flash-to-cell clustering algorithms are accurate enough for first-order investigation of geophysical variability. *[Boccippio et al 2002b, 2000a, 2000d; Williams et al 2000; Thomas et al 2000, Koshak et al 2000].*
9. Development of a unified HDF-based storage format for ground network validation data, following the OTD/LIS structural model. This format is applicable to: KSC/LDAR VHF data, MSFC/LMA VHF data, GAI National Lightning Detection Network LF data, GAI Long Range Network LF data, MSFC/TRMM-LBA LF data, and others. IDL-based HDF readers/writers for this data format have been written. A prototype ESML (Earth Science Markup Language) metadata document is also being developed for OTD/LIS data.
10. Communication of these results to the scientific community through either first or co-authorship of: nine (9) journal papers (in *J. Atmos. Oc. Tech., J. Geophys. Res., Geophys. Res. Lett., Mon. Wea. Rev., J. Appl. Met.* and *J. Atmos. Sci.*), eight (8) conference presentations (AGU, ICAE and IAMAS), two (2) seminars, and annual progress reports to the TRMM Working Group.

3. Detailed results

3.1 Calibrated dataset release

3.1.1 Performance modeling

As discussed above, the prelaunch calibration and performance estimates followed this basic methodology:

1. Sample a “truth” distribution of optical pulse radiances within lightning flashes (from an optical pulse sensor aboard the U2 aircraft).
2. Determine the minimum detectable radiance of the OTD and LIS CCD arrays as a function of applied threshold.
3. Assume comparable sampling geometry between the U2 and OTD/LIS, assume a nominal operating threshold for the sensors, and thus predict a nominal operating flash detection efficiency.

This approach was suitable for basic instrument design, and yielded the 90% LIS flash DE predic-

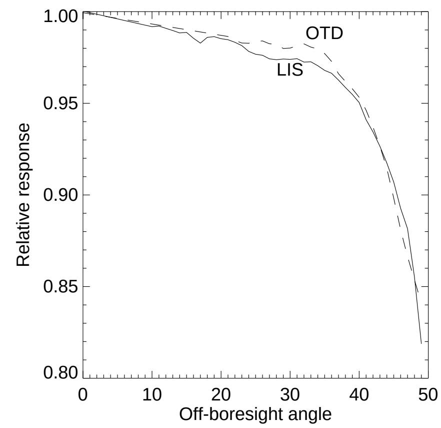


Fig. 1: Mean response of the OTD & LIS across their angular FOV, from calibration data.

tion. However, the assumptions hide a significant range of variability, which, if not considered, leave ground validation results completely without an appropriate context. The OTD and LIS performance varies across their FOVfor a number of reasons:

1. The transmission through the lens/filter assembly falls off up to 15% at the corner of the angular field of view (Fig. 1).
2. Also at the corners of the field of view, the lightning emissions being observed are scattered out the sides of clouds, not from the top surface. Modeling studies indicate that an appreciably smaller fraction of light scatters from cloud sides. The U2 truth dataset, however, was primarily nadir-viewing.
3. The CCD subarrays themselves (or rather, the amplifiers) vary in performance and sensitivity, as revealed in the full laboratory calibration data (Fig. 2).

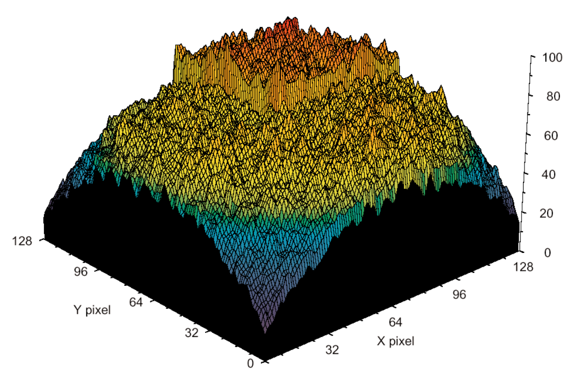


Fig. 2: Bootstrapped demonstration of LIS CCD subarray variability in sensitivity.

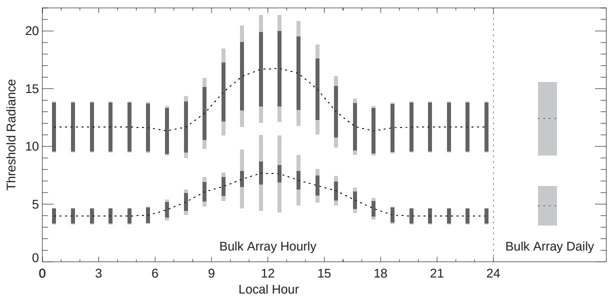


Fig. 3: Diurnal cycle of applied instrument threshold radiance for OTD (upper) and LIS (lower). Grey bars indicate +/- 1 std. dev. due to CCD variability (dark) and background scene intensity (light). Right panel shows errors associated with assumption of a single, diurnally invariant threshold.

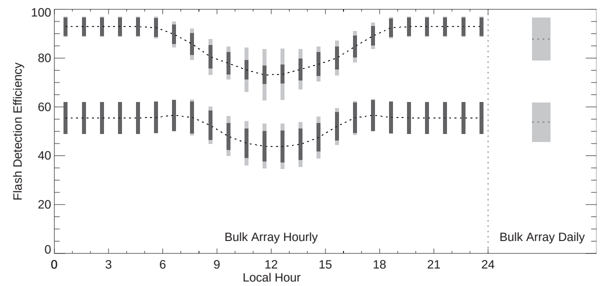


Fig. 5: Diurnal cycle of maximum predicted lightning flash detection efficiency for OTD (lower) and LIS (upper). Error bars are as in Fig. 3.

4. The size of U2 "truthing" pixels was variable and not always consistent with OTD or LIS pixel footprint size. This limits the transferrability of the "truth" mapping.
5. Perhaps most importantly, the instruments have an adaptive sensitivity, which is reduced during daytime hours. The sensitivity is a direct function of the background scene intensity, which is not regularly recorded with the data. To fully model the operational performance, the distribution of this background radiance must be considered.

Effects 1,2,3 and 5 have been incorporated into a complete performance model of the OTD and LIS sensors. The background radiance distribution is 'bootstrapped' from the subset of times in which observed transient pulses are concurrent with a recorded background scene. This yields a diurnal cycle of: (1) Nadir-equivalent applied threshold radiances (in true units, rather than instrument counts) (fig 3), (2) effective instrument signal-to-noise ratio (SNR) (fig 4) and (3) Maximum possible instrument flash detection efficiency (fig 5). Most importantly, this also yields the intrinsic measurement *variance*, given that background scene radiance is not regularly reported, and that adjustment of data based on its relative location wihtin the array during an overpass is impractical. This variance has also been decomposed into instrument-related (FOV variability) and background- related (adaptive sensitivity variability) components.

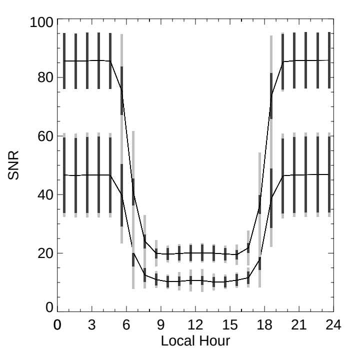


Fig. 4: Diurnal cycle of OTD (upper) and LIS (lower) signal-to-noise ratio, following Christian et al (1989).

The resulting performance model was presented in *[Boccippio et al, 2002a]*, and forms the basis for the calibration applied to the official gridded climatologies. This study also compared the predictions against ground-based validation (Table 2, and see below) with consistent results. It also predicts the relative detection efficiency differences between the OTD and LIS, which is almost exactly bourne out by the ratio of the observed climatological data.

The final consideration, effect (4) (lack of parity between U2 and OTD/LIS pixel sizes) is, nonetheless an important point, and could yield a small net adjustment in the DE predictions. Unfortunately, accepting that this effect exists means that the U2 dataset can not formally be used as a definitive "truth" mapping. As such, an alternative approach was derived which uses the LIS measurements themselves as a controlled-geometry, bootstrapped "truth" dataset. This approach capitalizes on the fact that one LIS CCD subquadrant is *significantly* more sensitive at night than all other LIS CCD subquadrants during night or day, and than all OTD pixels (Fig. 2). Hence the *relative* numbers of lightning pulses, strokes and flashes observed, in CCD coordinates, at various pixels and various threshold radiances (now known), provide an alternate "truth" mapping, *relative to the peak LIS subquadrant nighttime results*.

Study	Sensors	τ	Flashes	$\mathcal{F}$ Result	$\mathcal{F}$ Prediction
Boccippio et al 2000a	OTD/NLDN	All	4571	$\leq 55\% - 70\%$	$\leq 46\% - 62\%$
Thomas et al 2000	LIS/LMA/NLDN	0116	128	84%	$\leq 93\% - 97\%$
Ushio et al 1999	LIS/LDAR/NLDN	1740	122	$\geq 57\%$	$\leq 83\% - 94\%$
Koshak et al 2000	LIS/LDAR/EFM/NLDN	$1800 - 0500$	77	92%	$\leq 87\% - 97\%$
Boccippio et al 2000a	OTD/NLDN	All	4571	$\pm 2 - 7\%$ day/night	$\pm 6\%$ day/night
Boccippio et al 2000b	LIS/OTD	All	3.3×10^6	LIS $= 1.65 \times$ OTD	LIS $= 1.67 \times$ OTD

Table 2: Comparison of ground-based validation results (column 5) against predictions from the complete performance model (column 6) results shown in Fig. 5.

The first requirement for this approah is that pixel trigger conditions for off-boresight observation must first be expressed in terms of the nadir-viewing geometry of the bootstrapped truthing dataset. This result was presented as eq (14) of *[Boccippio et al, 2002a]*. The second requirement is a formalism to map relative pulse (pixel) detections to higher order detection efficiencies (i.e., those for strokes and flashes). This can be achieved through straightforward binomial modeling (i.e., the likelihood of observing a higher order quantity such as a flash is a binomial function of the likelihood of observing a lower order quantity such as a pulse, given a known distribution of the number of lower order components per higher order component; Fig. 6).

This sounds rather complicated, but the key finding is that the adaptive sensitivity of the instruments is actually a boon: it creates an overdetermined sampling system in which parameters of interest (maximum possible flash detection efficiency as a function of threshold radiance) is, in principle, invertible from the composited observations. The only obstacle is the stability of the inversion process itself, which is discussed below. These results will be included in a follow-on paper to *[Boccippio et al, 2002a]*, currently in preparation.

$$B(1, \hat{n}_{g/f}, D_g(I_0))D_f(I) = B(1, \hat{n}_{g/f}, D_g(I_0)D_g^*(I))$$

$$B(1, \hat{n}_{e/g}, D_e(I_0))D_g(I) = B(1, \hat{n}_{e/g}, D_e(I_0)D_e^*(I))$$

$$B(\nu, n, p) = cumulative\ binomial$$

$$\hat{n}_{x/y} = true\ number\ of\ x\ in\ y$$

$$D_y = actual\ detectability\ of\ y$$

$$D_y^* = relative\ (observed)\ detectability\ of\ y$$

$$I_0 = lowest\ instrument\ radiance\ threshold$$

$$I = radiances\ above\ threshold$$

$$e, g, f = events,\ groups,\ flashes$$

$$1\ free\ parameter, D_e(I_0)$$

Fig. 6: Reduced formalism for the "bootstrap" approach of OTD/LIS detection efficiency inference.

3.1.2 Cross-calibrated dataset

The cross-calibrated and combined OTD+LIS dataset is illustrated in Fig. 7-10. Fig 7 shows the applied detection efficiencies for LIS and OTD, implemented as a function of local hour (both instruments) and date of mission (OTD only, due to in-mission threshold changes). A further spatially-dependent reduction was applied over the South Atlantic Anomaly for OTD, derived from the cross-normalization (the area of impact of the SAA for LIS is about 1/4 the size of that for OTD, due to its lower orbit, thus for all regions outside the LIS SAA core, the ratio of the independent climatologies serves as an estimate of OTD DE reduction). The SAA for LIS affects only a small area near Sao Paulo, Brazil, and without total lightning ground systems in that location, has indeterminate effects on the sensor.

Fig. 8 shows the annualized, calibrated combined climatology, along with seasonal breakdowns. The 'annual cycle' climatology (smoothed using a 55-day operator; see below) is shown in Fig. 9 and is clearly stable enough for regional decomposition. Fig 9 also shows the annual cycle for a "point" (5x5 deg) location, the EPIC-2001 experiment domain in the East Pacific, a relatively low flash rate region which might be expected to be problematic. 110-day smoothed OTD, 49-day smoothed LIS and 30-day smoothed National Lightning Detection Network / Long Range estimates are overlaid. The results of this study provided cross-calibrations of all three instruments, and even with the sampling limitations, there is reasonable coherence in the annual cycles.

Fig. 10 illustrates the benefits of constructing a

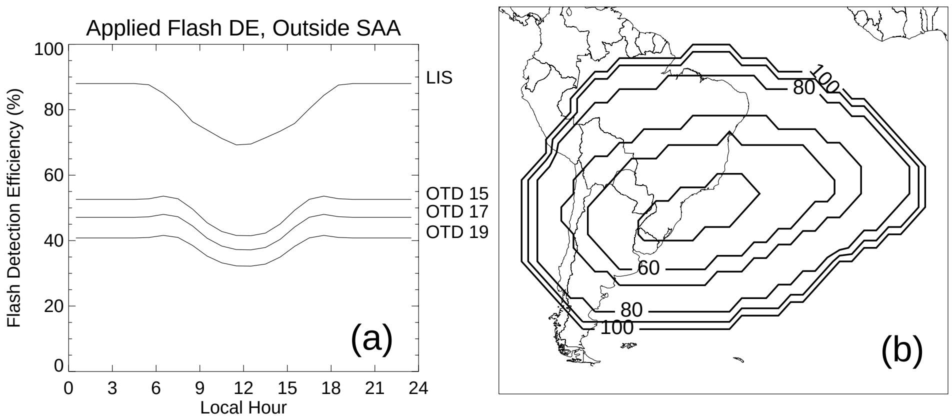
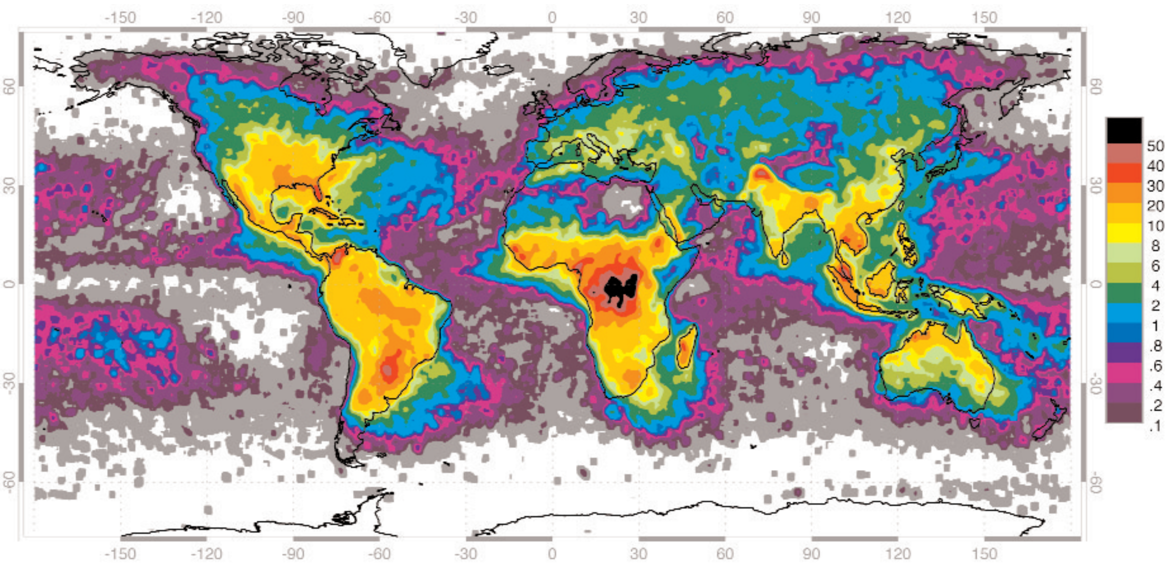
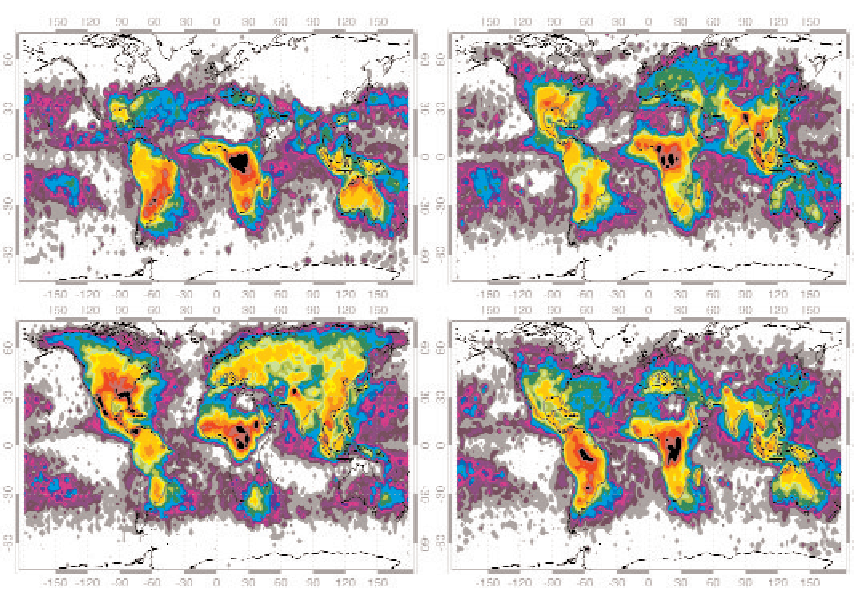


Fig. 7: Detection efficiencies applied in the combined, cross-calibrated climatologies. Left, diurnal variability; Right, further OTD SAA adjustment (% reduction over nominal DE).





DJF

MAM

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Fig. 8: Calibrated, merged climatologies, from 5 years of OTD and 3 years of LIS data, in units of flashes / km² / yr. Top, annualized climatology. Left, seasonal breakdowns (same units).

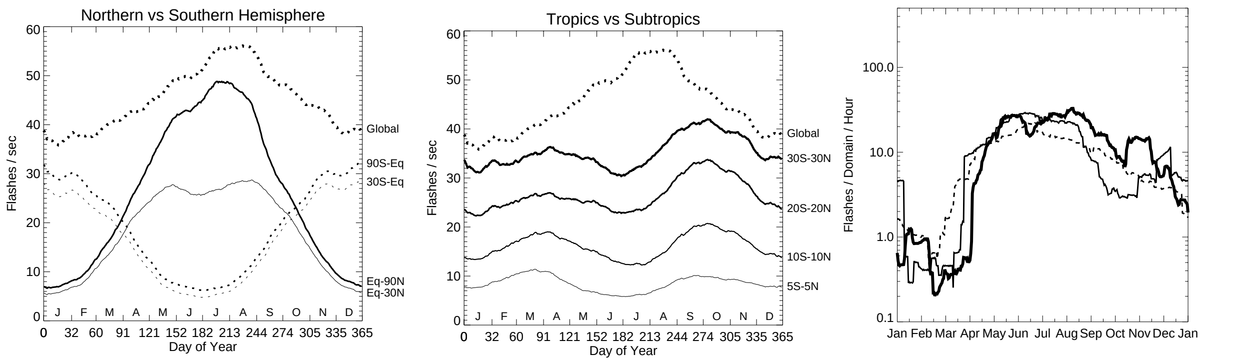


Fig. 9: Regional (hemispheric, left; zonal, center) resolution of the climatological annual cycle in the combined dataset (55-day smoothing applied). "Point" (EPIC domain centered at 95W/10N) resolution of the annual cycle by independent and cross-calibrated LIS, OTD and National Lightning Detection Network - Long Range climatologies (49, 110 and 30 day smoothing, respectively).

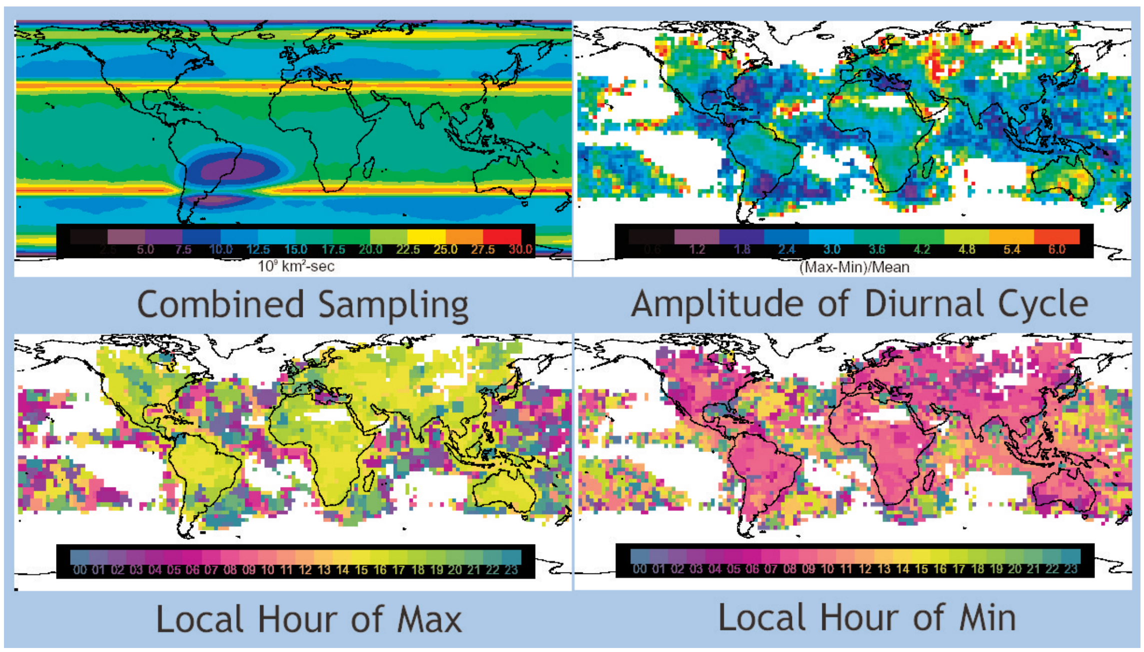


Fig. 10: Decomposition of the local hour diurnal cycle phase and amplitude, illustrating benefits of increased sampling in the combined dataset.

merged climatology; the sampling from either mission alone was inadequate to attempt to address "second order" variability such as the phase and the amplitude of the diurnal cycle, but upon merging of the datasets, enough coherence is found to identify broad regional trends.

3.2 Deconvolution of instrument response; flash rate distributions

As with many other satellite observations, the instrument response of the OTD and LIS must be considered when inferring distributions of observed properties, such as the "true" number of pulses per flash, or the "true" spectrum of storm cell flash rates. Traditional inversion methodologies (i.e., use of a response kernel; fig 11) are completely applicable here.

For example, consider the need to infer the "true" distribution of the number of pixels per stroke, given a pulse detection efficiency *p*. (This is a necessary input to the boostrap performance model, above). The instrument response kernel can be constructed

OBS — RESPONSE KERNEL — TRUTH

$$\underbrace{g(y)}_{\text{OBS}} = \int_0^\infty \underbrace{K(x,y)}_{\text{RESPONSE KERNEL}}\underbrace{f(x)}_{\text{TRUTH}}dx$$

Fig 11: Traditional "response" kernel used in satellite inversion techniques. For OTD/LIS, the instrument response kernels are statistical, rather than physically-based functions.

Example: Number of pixels / stroke

Fundamental distribution for assessing:
LIS daytime performance, OTD performance, LMS/GEO performance

$$P(n_{obs_i}) = \sum_{j=i}^{\infty} \frac{P(n_{obs_i}\ from\ n_j)}{P(anything\ from\ n_j)} P(n_j)$$

Kernel follows from Bayes Theorem, $P(n_{obs} \mid\ something\ was\ detected)$,
and from binomial functions, $P(n\ successes\ in\ m\ samples\ with\ success\ rate\ p)$:

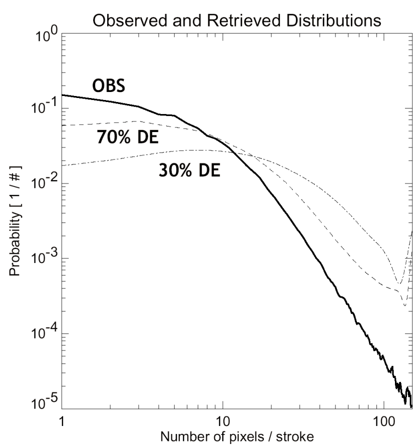
$$P(n_{obs_i}) = \sum_{j=i}^{\infty} \frac{j!p^i(1-p)^{j-i}}{i!(j-i)!(1-(1-p)^j)} P(n_j)$$

i.e., $\vec{g} = \vec{\vec{K}}\vec{f}$, and normal equations solution is $\vec{f} = (\vec{\vec{K}}^T\vec{\vec{K}})^{-1}(\vec{\vec{K}}^T\vec{g})$

Fig. 12: Basis for the OTD/LIS 'resonse kernel' for inference of the 'true' distribtion of number of pixels per stroke, or number of strokes per flash.

by application of Bayes theorem and the binomial functions (fig 12). Of course, since the binomial functions contain little high frequency content, additional constraints upon the inversion must be applied, but these are readily available and physically justifiable (fig 13). This yields stable solutions which are a function of a single free parameter (*p*, the pixel detection efficiency), which itself is determinable from either the U2 or follow-on field observations (and in principle is inferrable from the bootstrap approach).

A similar problem applies to the inference of the "true" spectrum of storm cell flash rates, given our observed spectrum. Since the OTD/LIS have finite, non-unity detection efficiency, and a limited dwell time over individual storms, the 'low end' of the observed flash rate spectrum is biased (i.e., our cell detection efficiency drops monotonically for lower and lower "true" flash rate cells).



$$\vec{f} = (\vec{\vec{K}}^T\vec{\vec{K}} + \gamma\vec{\vec{1}} + \alpha\vec{\vec{I}})^{-1}(\vec{\vec{K}}^T\vec{g} + \gamma\vec{1})$$

Fig 13: Stabilization and conditioning of the number of pixels per stroke inversion by application of physically justifiable constraints (probabilities must sum to 1; minimization of power in solution).

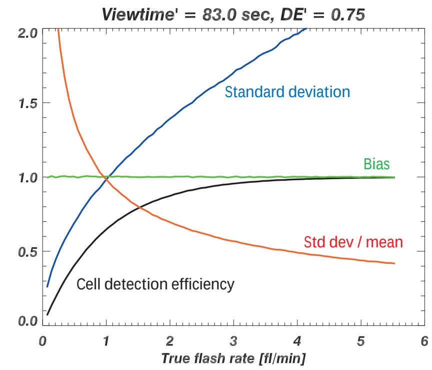


Fig. 14: Assumption of Poisson-distributed inter-flash durations yields estimates of the cell detection efficiency as a function of true cell flash rate (black), as well as the point estimate error, which is less than 50% for most flash rates (red).

This can be handled by making the (reasonable) assumption that interflash times in cells are Poisson distributed. An immediate consequence of this assumption is that the cell detection efficiency (as a function of true flash rate) is determinable, as is the variance in the flash rate observation (as a function of true flash rate) (fig 14). A second consequence is that that the Poisson distribution forms the response kernel for inversion of the true flash rate distribution itself (fig 15). Again, the Poisson functions contain little high frequency content, and the inversion must be constrained and conditioned, but the problem is now fundamentally tractable.

The conclusion is thus that event-based observations from the OTD and LIS are amenable to the same inversion processes used in traditional satellite retrievals; the kernels (instrument response) are simply *statistical* rather than *physical* convolutions.

The inference of storm cell flash rate distributions is of fundamental interest in LIS-based science: now that climatological (bulk lightning production) is well quantified, its decomposition into storm cell

$$P(f_{obs_i}) = \int_0^{\infty} \Phi_i(f(x))P(f(x))dx$$

Fig. 15: Assumption of Poisson-distributed inter-flash durations also yields the response kernel to "unbias" the observed per-cell flash rate distribution.

frequency of occurrence and intensity is the next 'level down' of interest in understanding what LIS tells us about the convective spectrum.

The issue of algorithmic association (clustering of LIS-observed optical pulses into nominal flashes, and of nominal flashes into nominal storm cells) was an important goal of the validation effort. Some progress has been made on this front.

At the lowest level (pulse to flash clustering), evidence that the applied OTD algorithms provide 'reasonable' results were presented in *[Boccippio et al, 2000d]*, and application of a similar approach suggests that the impacts on LIS are less than a few % error. This was corroborated during individual case studies *[Thomas et al, 2000; Koshak et al, 2000]* in which nominal LIS flashes were qualitatively consistent with VHF-based 3 dimensional maps of lightning channels. An important result of the VHF/TOA 'validation of the validation sensor' studies *[Boccippio et al, 2000b, 2000c]* was a large-sample estimate of the distribution of actual flash durations (fig 12b of *2000b*). This confirms that a nontrivial number of actual flashes have durations in excess of 1 sec. Given the possibility of long-duration gaps in optical pulse measurements within flashes *[Thomas et al, 2000]*, and the distribution of cell flash rates, in which flash rates of > 1/sec are certainly possible (fig 16), it is apparent that the very nature of the observational technique will lead to some cases where flashes are simply unable to be 'disaggregated' from the pixellated optical pulse observations. This is a known limitation which should be considered when investigating the 'tail end of the distribution' of OTD or LIS flash rates.

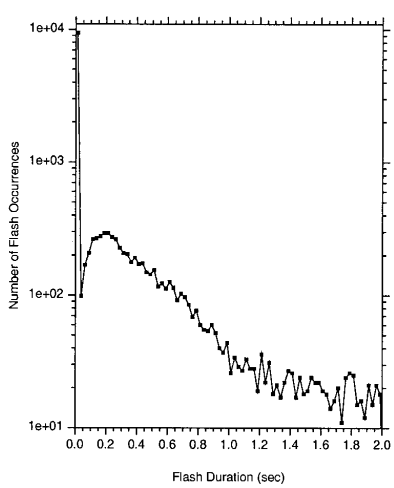


Fig. 16: Distribution of actual lightning flash duration, as estimated from KSC LDAR observations within a domain over which performance should be stable.

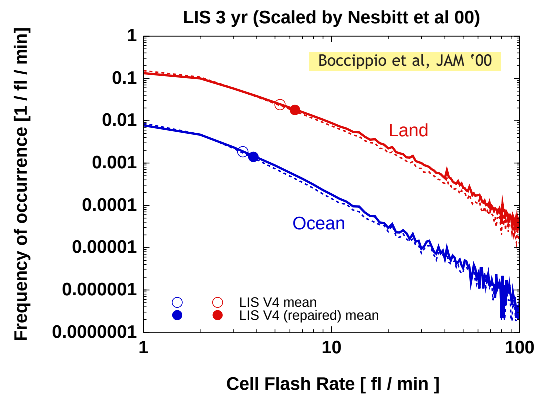


Fig. 17: Observed per-cell flash rate distributions over land and ocean (spectra in this plot have not yet been unbiased by the technique of Fig. 15). Results before (dashed) and after (solid) a logic bug in the LIS cell clustering algorithm was repaired; the impact is minimal.

At the flash-to-cell clustering level, progress has been more qualitative. First, it has been determined that a minor algorithmic 'bug' (deviation from the algorithm specifications) in the LIS v4 and OTD clustering algorithms has minimal impact on the resulting flash rate distributions (fig 17). Second, *[Williams et al, 2000]* have compared the LIS storm cell clustering algorithm against a much simpler aggregation approach, that of simply dicing the earth into fixed-registration-grid "patches" in which lightning either occurs or does not occur. Interestingly, the salient features of the flash rate distributions are relatively insensitive to the clustering approach. This is another example in which the very wide dynamic ranges of the actual geophysical distributions (20 dB of flash rate variability with 40 dB of frequency-of-occurrence variability, fig 17) buffer the interpretations against the nuances of individual algorithms. While these wide dynamic ranges pose severe problems from a sampling and variance standpoint, they fortunately mitigate the impacts of individual algorithmic choices.

3.3 Sampling and smoothing

3.3.1 Sampling, Diurnal Bias and Variance

Issues of sampling, binning and smoothing are very important in determination of statistically defensible construction of higher-order OTD and

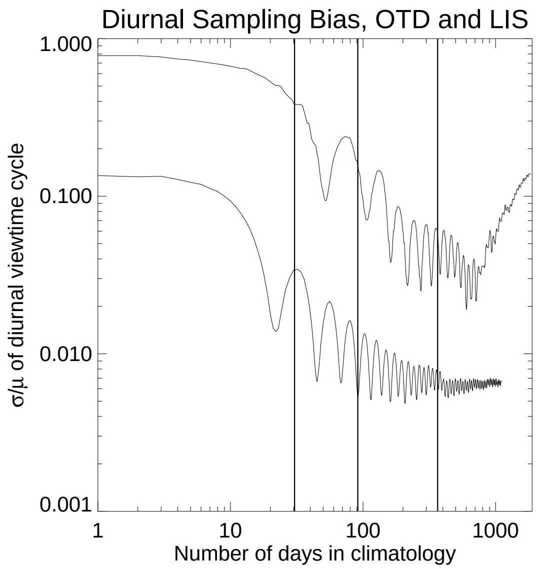


Fig. 18: Diurnal sampling "inequity" in climatological composites of varying duration. This inequity yields a susceptibility to bias, modulated by the amplitude of the actual diurnal lightning cycle.

LIS data products for the user community.

Temporal smoothing is by far the most important consideration. The precessing orbits of both instruments' host platforms lead to unequal sampling over the course of a local hour diurnal cycle. This is especially critical given the pronounced diurnal cycle of lightning activity, especially over land (perhaps a larger cycle than with any other TRMM observable). Compositing of data on time scales other than the intrinsic revisit cycles can lead to substantial diurnal aliasing and bias.

Fortunately, both sensors continuously record their space-time (i.e, *(x,y,t)*) viewing, and an assessment of the bias potential is readily tractable. Fig 18 shows the diurnal "inequity" in sampling for composited global data of increasing durations for both OTD and LIS. The minima correspond to the natural revisit cycles of the platforms (23 days for LIS, 55 days for OTD), with 30, 90 and 365-day composites denoted by vertical bars. 30-day composites (a "natural" product interval) clearly lie at the *least* favorable position for LIS; 60-day composites do not fare much better. 90-day composites lie near a LIS optimum, and correspond to a reasonable bias reduction for OTD.

In composited climatologies using both sensors, the OTD sampling (roughly 4x that of LIS) dominates, and the natural OTD 55 day cycle dominates. Qualitatively, it was found when processing full-OTD mission data that due to platform down-time, 110-day compositing or moving averages were the shortest interval which smoothed out obvious sampling-related bias or noise. A 110-day moving average has thus been recommended as a conservative window when using the annual cycle climatology.

This analysis only covers the *susceptibility* to bias, which is in turn modulated by the strength of the actual diurnal cycle. It may be overly cautious for ocean regions, but the infrequency of lightning occurrence over oceans places other constraints on sampling there.

The natural precession cycles thus define the lowest potentially viable compositing windows. In order to determine whether they *are* viable, the purely sampling-related variance must be understood. The results of section 3.1provide one component needed for this analysis, the intrinsic measurement variance. From this, minimum possible variance in the composited data can be estimated, as a first check on the viability of the time window. The much larger component is the actual varaiance of the population being sampled. The results of section 3.2 provide some useul information for some types of products (conditionally sampled storm flash rates), i.e., that this population variance does not appear to have significant spatial variability. The more general result (the sampling variance for bulk flash production estimates) is contingent on the actual frequency of occurrence of storm cells, and is still being pursued. The problem of estimating error bars is thus not yet completely solved, although signficant progress has been made on the components of a traditional variance decomposition.

This is also more than just a 'second order' problem. From fig 18, it is apparent that the diurnal bias susceptibility from the OTD mission actually *increases* when more than 2 years of mission data are composited; this is due to increasingly frequent Microlab-1/OV-1 platform down-time. It is thus not immediately apparent that a 5-year OTD climatology necessarily has lower variance than a 2-year OTD climatology; only a complete variance decomposition can answer this question.

3.3.2 Spatial Smoothing

The wide dynamic range in thunderstorm frequency of occurrence also complicates generation of global maps of 'higher order' parameters, such as mean cell flash rate, mean event/stroke/flash radiance, etc. The problem here is complicated by the wide dynamic range of these parameter distributions themselves (often lognormal) and the difficulty in robustly estimating population means with small data samples.

Traditional fixed-registration-grid mapping approaches are an inadequate solution to this problem, even at very low resolution. The fixed-grid averaging approach assumes that for each grid cell, a population mean can be estimated, but no information on quality is readily determinable (since the population variances themselves are intrinsically large). This is illustrated in Fig 19 (upper right panel), and demonstrates that this compositing approach effectively assumes that spatial decorrelation from grid cell to grid cell "trumps" the sampling-related variance. Outliers in low-frequency-of-occurrence regions such as oceans are common, and there is no objective way whether or not to determine whether these should be, e.g., used in quantitative cross-correlation with other observables. This approach is also 'overkill' in high frequency-of-occurrence regions, and smears out actual geographic contrast which is often of considerable interest.

Some level of contrast can be regained by oversampling (i.e., constructing a very high resolution gridded map, then applying a spatial moving average; Fig 19, lower left). This approach is completely defensible given the implicit assumptions in the low resolution gridding approach (i.e., if we are prepared to accept one, we must be prepared to accept the other). However, it does little to fix the problem of undersampled outliers.

A far more sensible solution in a high-contrast, sampling-limited situation such as this is to use an adaptive resolution approach. Under this approach, a very high resolution base map is constructed, and a target sample size (i.e., target estimate variance) is prescribed, and for each location, the spatial smoothing domain (number of adjacent grid cells) is adaptively increased until the target sample size

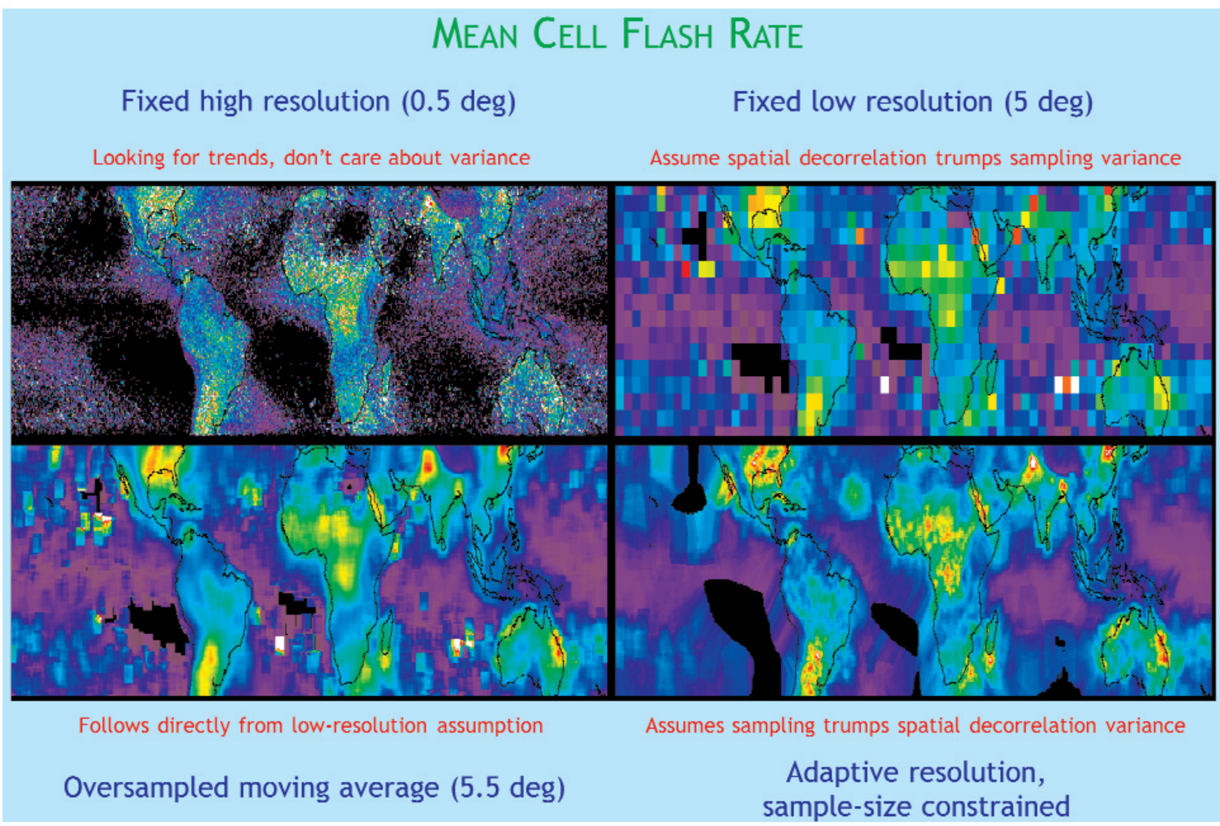


Fig. 19: Various approaches to spatial aggregation of conditionally sampled parameters, such as the mean per-cell flash rate. An adaptive resolution approach (lower right) yields roughly 'constant variance' maps which suppress bogus outliers and preserve regional contrast, where it can be supported by the sampling.

has been met. This, loosely, constructs "equal variance" maps, in which spatial contrast is objectively preserved *and* sample-size-related outliers are mitigated (Fig 19, lower right). The implicit assumption here is that sampling related variance "trumps" spatial decorrelation-related variance, a situation which very likely holds for the lightning problem. The only downside to this approch is a tendency towards "nearest neighbor filling" in high frequency-of-occurrence-gradient regions (e.g., the east Pacific, east Atlantic), although this could easily be removed by additional logic filters (e.g., construct a point estimate only if the samples are evenly distributed about the adaptive domain).

This approach has also been applied to mean observed pixel radiance (Fig 20); here, the benefits over low resolution gridding or moving-average smoothing are even more apparent. Interestingly, this parameter appears to have nontrivial global variability, presumably corresponding to differences in cloud optical depth and relative lightning-cloud geometries (and perhaps contributions from variability from actual optical emission). This has an important implication for the instrument DE estimates: since the prelaunch optical pulse sensor "truth" dataset was constructed from storms sampled in the southeast U.S., this "truth" mapping may not be globally applicable (if the population means are higher elsewhere, lightning is "more detectable" by the instruments). The 'good news' is that the bulk of this variability appears to occur in lightning-sparse regions, and that if anything, instrument detection efficiency in these regions should be higher than that estimated using the SE U.S. database. Since the instrument DE already appears to be very high, there is not much "room" for additional error, i.e., at some point, it will cap at unity. Because, however, of this apparent natural spatial variability, there is *no way* to assess its impacts on the calibration, shy of direct and in-situ ground or aircraft validation. Fig 20 does indicate which regions would be prime targets for such efforts, although most fall in locations unlikely to be the sites of future field campaigns (or of field campaigns of adequate duration to provide additional constraints).

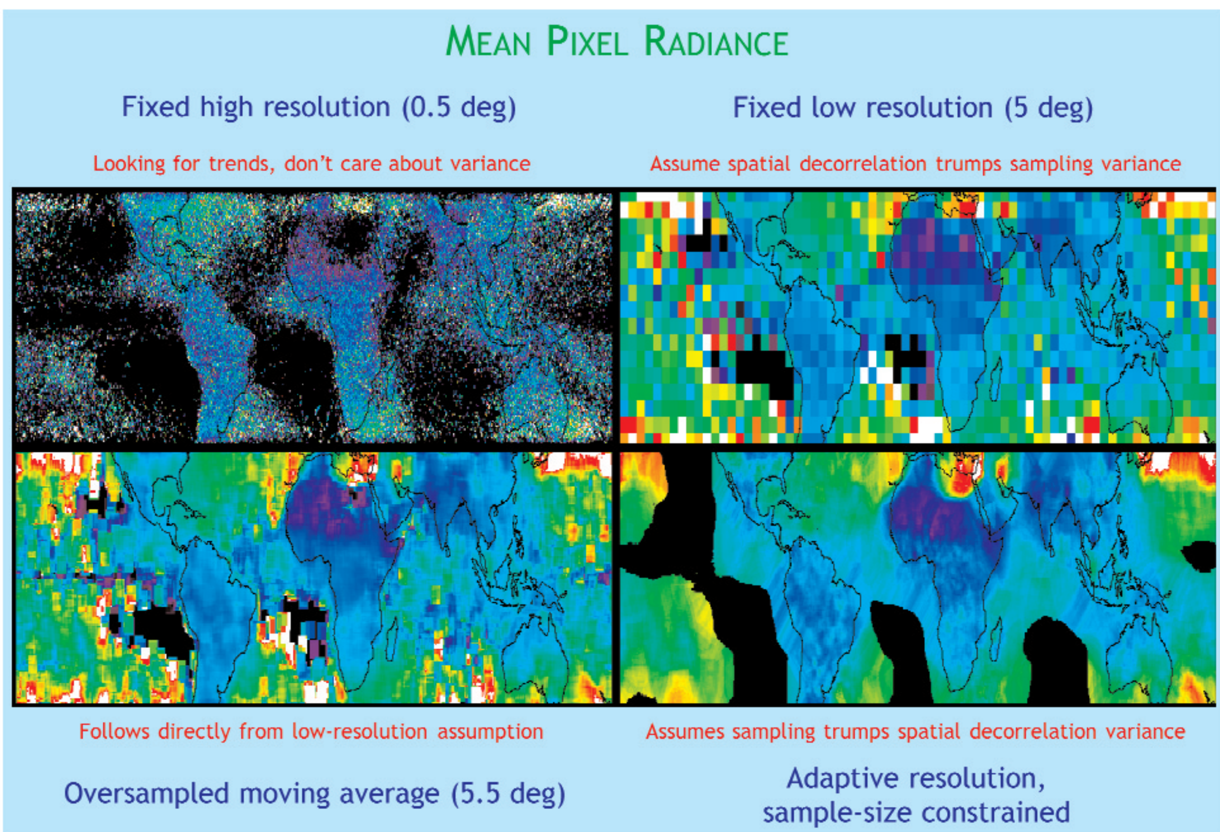


Fig. 20: As in Fig. 19, but for mean pixel radiance. Suppression of bogus outliers in the adaptive resolution approach is even more dramatic with this parameter.

3.4 Ground validation

The approach towards ground validation evoloved over the course of this study, and its relative importance was diminished over the original proposal (although it still forms an important cornerstone of the validation results). Several factors contributed to this decision:

1. Other research teams, including Krider et al (also funded under 97-MTPE-03) were pursuing intensive ground validation efforts. We decided to collaborate with and support these teams, rather than make ground validation a primary effort of this study.
2. No other teams were pursuing the OTD/LIS performance modeling and cross-calibration (also a component of the original proposal), and this approach seemed the fastest route to an operationally useful instrument calibration (if corroborated by ground validation, which it was). Early development of the performance model also indicated that without a complete model in place, the results of isolated and finite-scope ground validation case studies would simply lack enough context to provide self-sufficient results for operational calibration.
3. Key ground validation systems were delayed in their deployment or utility; improved algorithms for processing the TRMM-LBA ground network data have only recently become available, while the MSFC-LMA VHF ground network was delayed nearly two years in deployment due to MSFC administrative and legal hurdles in executing MOU's with property owners of the twelve receiver sites. While these data will be analyzed, it would not have occurred prior to the end of the 97-MTPE-03 POP, so effort was redirected towards existing validation networks.
4. It was also quickly determined that many existing or new ground validation systems simply lack adequate quantitaive demonstration of their *own* performance characteristics, making identification of acceptable space-time cross-comparison domains difficult. A decision was thus made to devote some effort to "enabling" validation of the validation sensors, which will carry benefits well beyond the present study.

These caveats aside, several useful concrete results were nonetheless obtained:

1. *Validation of validation systems*. One of the most useful results is the complete performance modeling and validation of the useful range of VHF/TOA total lightning mapping systems, such as the NASA/KSC LDAR network. These networks are becoming a backbone of much current ground-based research and validation (new networks are being deployed at MSFC and NSSL, a prototype network exists at the New Mexico Institute of Mining and Technology and was deployed during the STEPS field campaign, and two commercial systems have been deployed by Global Atmospherics, Inc., including one at Dallas/Ft Worth International Airport). The results of this study were presented in *[Boccippio et al 2000b,c],* and for the KSC LDAR network, identified a maximum useful range (stable flash detection efficiency) of 90 km from the network centroid (fig 21). Extension of the useful range to its maximum justifiable extent is extremely important for ground validation, given the infrequency of LEO instrument field-of-view intersections with ground-observed storms.
2. *KSC LDAR: Vertical distribution of VHF*

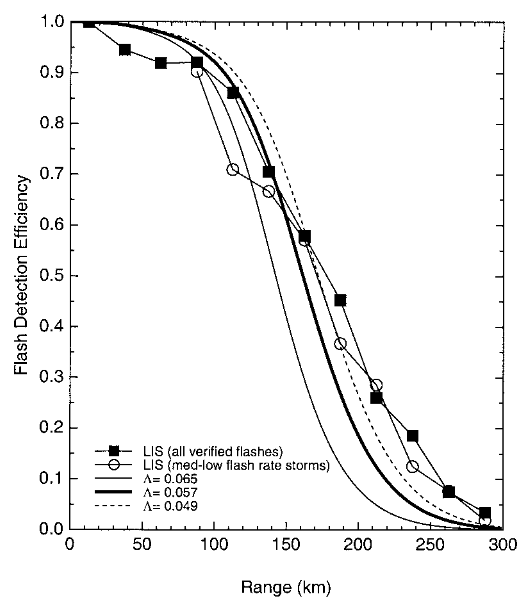


Fig. 21: Modeled and LIS-verified KSC LDAR flash detection efficiency vs range. A 90 km cutoff appears to be the largest possible domain for controlled individual case-study intercomparisons.

sources associated with optical pulses. A database of paired LIS- and LDAR-observed lightning flashes, and of LIS “misses”, was a byproduct of result (1). From this, the vertical distribution of VHF sources (emissions during lightning channel formation) in flashes observed and not observed by LIS was determined. This corroborated the expected result that most LIS optical pulses are associated with the growth of the upper branches of intracloud channels, although CG channels are also detected. We then collaborated with T. Ushio (Osaka University) who conducted a similar study, as reported in *[Ushio et al, 1999].* This study also demonstrated the acceptable location accuracy of the LIS sensor, as well as illustrating some cases where the observed optical pulses (near dusk) were actually scattered off of the tops of low-lying, adjacent clouds. This puts statistical estimates of LIS location ‘errors’ in context; these are not necessarily always attributable to either TRMM attitude/ephemeris errors or LIS lens transformation matrix uncertainty. Finally, we provided support to Krider et al in their rigorous cross-sensor study incorporating LDAR, the KSC electric field mill network, the National Lightning Detection Network and the LIS. By diagnosing the exact viewing conditions and instrument/platform status during their studied overpasses, a number of “truth” flashes were ruled out as not justifiable, given known/documented instrument/platofrm conditions. Such careful treatment can make up to a 10-20% difference in inferred detection efficiency (and is justifiable, since these diagnostics are routinely recorded with LIS data and considered during data compositing). Their results were presented in *[Koshak et al, 2000].*

3. *NMT LMA: Vertical distribution of optical pulse sources, additional DE estimates, optical pulse “duty cycle” during flashes.* Collaboration was also initiated with P. Krehbiel and R. Thomas of NMIMT, during their demonstration deployment of the next-generation VHF/TOA systems in Oklahoma. A LIS overpass with 160 flashes was isolated and these flashes manually segregated through examination of the joint LIS/LMA data. Conclusions were similar to the Ushio study. The NMT/LMA also has significantly higher VHF sensitivity, and detailed channel structures were more readily available. 2 ms-timestep animations of LMA and LIS overlays were constructed for each flash. We then collaborated with R. Thomas on a more detailed study, presented in *[Thomas et al, 2000].* One of the interesting outcomes of this study was identification of CG flashes which were detected by LIS, but since they were comprised mainly of low-altitude channels, had nearly 800 ms of ‘dead time’ between successive pulses. This has relevance for the LIS pulse-to-flash clustering algorithm, which considers a dead time of 333 ms as the cutoff after which a new nominal flash datum is initiated. While such occurrences are rare, they illustrate the fundamental ambiguity in trying to count higher order entities such as “flashes” whose spatial and temporal evolution distributions span a wide dynamic range and whose occurrence rate (in high flash rate storms) may stress the limits of an optically-based approach (even with significantly higher sensor resolution, flash optical output is still multiply-scattered throughout the volume of the cloud, which is the ultimate limiter in discriminating flash substructure).
4. *GAI Long Range network: identification of a suitable cross-comparison domain.* A climatological cross-comparison of OTD and GAI lightning detection network data was undertaken. For the long-range (offshore) network product, an expected (but heretofore unkown) decrease in network sensitivity is expected with increasing offshore range (due to signal attenuation) and with day/night status along the signal transit path (due to differential ionosphere heights). Without knowledge of the range over which sensitvity is stable, rigorous offshore cross-comparison could not be properly undertaken. The climatological comparison demonstrates an exponential decline with range past about 1500 km (Fig. 22), and demonstrates that only nighttime long range network data are stable enough for case study cross-comparison within that range. These results are also of considerable interest to the atmospheric chemistry community and data assimilation communities, who are forced to rely on long-

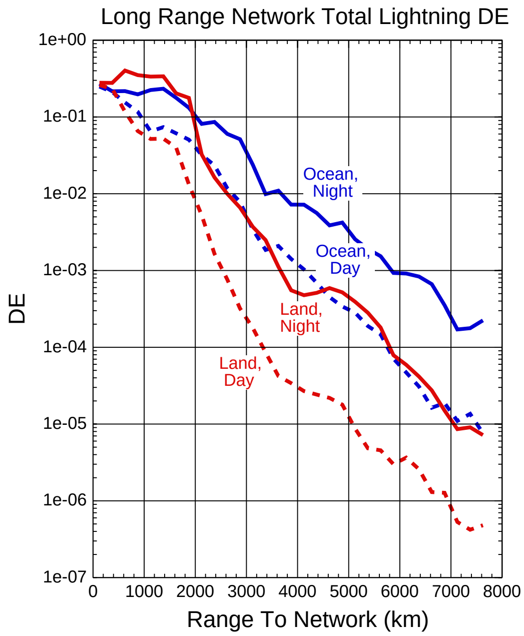


Fig. 22: Climatological inference of Natonal Lightning Detection Network / Long Range total lightning detection efficiency. Nighttime data within 1500 km range-to-network comprise a reasonably controlled domain for individual case studies.

range network data in absence of a continuously-monitoring satellite-based (i.e., geostationary) sensor. The results were reported by *[Boccippio et al, 1999, 2001b, 2001d],* and passed on to a collaborator, W. Boeck of Niagara University, who utilized them in several follow-on studies.

5. *GAI National Lightning Detection Network: determination of useful intracloud detection capabilities and signal*. This is more of a 'science' validation than a quantitative validation activity. The ability of the OTD and LIS to detect intracloud lightning was indicated by the prelaunch U2 data, and corroborated by the ground based results (2) and (3). However, validation can also be construed to mean verifying that we indeed extract useful science information from the additional signal provided by intracloud lightning. The same climatological cross-comparison used in (4) was applied over the CONUS, and from it the first-ever spatially resolved map of the intracloud:cloud-to-ground ratio was generated (Fig. 23). A key element of this study was an error analysis incorporating known uncertainty in the NLDN and OTD calibrations at the time. A clear maximum over the midwest U.S. was identified, just as would

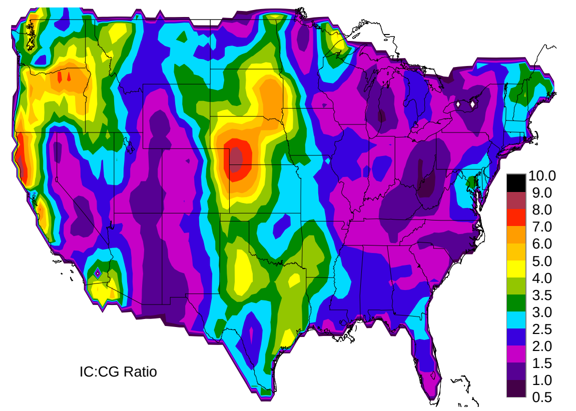


Fig. 23: Inferred intracloud : cloud-to-ground lightning ratio over the continental U.S., demonstrating utility of the additional intracloud lightning measurement capability of OTD and LIS. The signal is robust against likely uncertainty in either satellite or ground system calibration.

be predicted given current theories on the relationship between intracloud lightning and storm intensity (updraft strength), e.g., the 'elevated dipole' hypothesis. The extrema identified in the study were robust against possible uncertainty in instrument calibration. This thus comprises a science 'validation' of the incremental information content provided by total (especially intracloud) lightning data. The results were published in *[Boccippio et al, 2001a]* and featured in a Science@NASA article.

6. *Comparison with global meteorological parameters*. Also a 'science' validation, this study intercompared LIS lightning observations with large scale (ECMWF-derived) meteorological parameters, the gross moist stability and moisture convergence efficiencies of the 'continuously convecting' regions of the tropics. A reasonably monotonic and globally invariant relationship between lightning parameters and convective parameters has never before been demonstrated, although such a relationship is expected and indeed forms the basis for many LIS-related science applications. This study, while preliminary, demonstrated monotonic relationship (Fig. 24) between the *frequency of thunderstorm occurrence* and moisture convergence efficiency (the latter a key parameter in current quasi-equilibrium theories of tropical convective adjustment). While monotonic relationships between light-

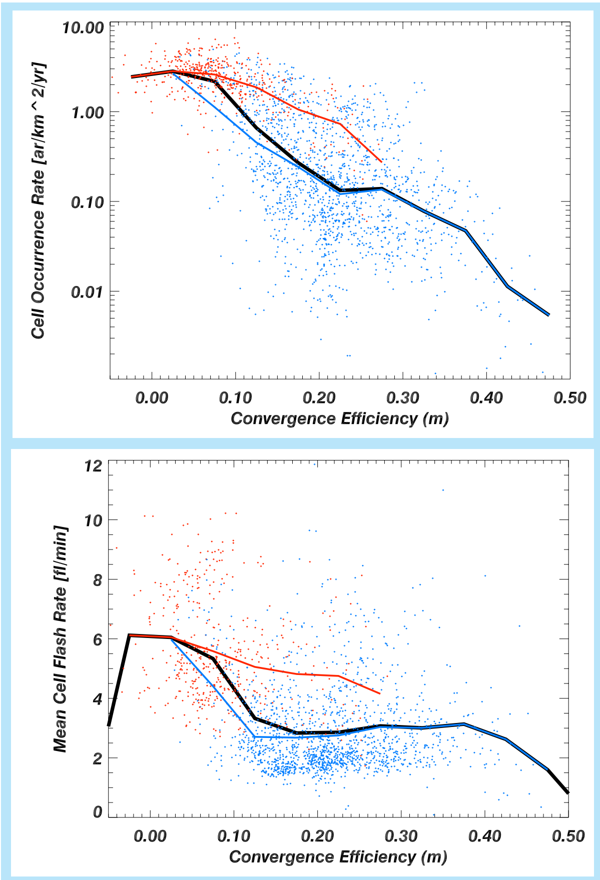


Fig. 24: Comparison between the thunderstorm frequency of occurrence and the moisture convergence efficiency of the tropical atmopsphere, a key parameter in quasi-equilibrium theories of tropical convective adjustment.

nign flash rate and convective storm parameters such as radar reflectivity or microwave brightness temperature are somewhat unsurprising, a relationship between lightning observations of the convective spectrum and the adjusted state of the atmosphere is important (if 'fuzzy' and indirect) corroboration of the utility of lightning measurements for global climate studies.

3.5 Data management and storage

In the process of accumulating and organizing relevant ground network validation data, it was realized that a common storage format would be both useful and tractable for the disparate datasets, which all comprise of one or more hierarchically related aggregates of station, stroke and flash data. The hierarchical relationship is very similar to that of the LIS data themselves; consisting of pulses, strokes, flashes and cells. To facilitate cross-comparison, am HDF format was designed for the ground data which is structurally very similar to the LIS data format, and a set of input/output libraries to read and translate data into this format were written. The OTD dataset was also converted from its original (somewhat messy) HDF data format to the much more logically-organized LIS data structure. This reduced the number of data storage formats and interface libraries to two, and allowed complete reusability of cross-comparison code.

An additional collaborative effort was initiated in the final year to write ESML markup tags for LIS and OTD data. ESML (Earth Science Markup Language) is an experimental description language (like XML or HTML), designed to allow universal, content-based input/output of Earth Science data regardless of storage format; the idea is that once a markup file is written, applications may import te data without custom interface libraries for each dataset. Sample data have been provided to the University of Alabama in Huntsville ITSC and a prototype markup file is expected imminently.

4. Continuing work

The following are efforts begun under this grant which will continue past the final POP, either funded directly by the LIS mission or performed on an as-needed basis to enable science-related NRA research (specifically, 99-OES-03):

1. *Bootstrap performance modeling.* The complete statistical analysis methodology for this effort (an extension and corroboration of the performance model) are concrete products of this research; the only remaining steps are the actual statistical analysis itself and documentation of the results. This will comprise a followon paper to *[Boccippio et al, 20002a]*. The PI rates this as high priority as it will contribute directly to design efforts for a proposed geostationary mission.
2. *LIS/OTD product variance estimates.* As described above, several of the key components of a complete variance decomposition are direct products of this research. The methodology for a complete decomposition has also been established, as well as a path by which the missing component (intrinsic population variance) can

be estimated. The PI rates this as high priority as it is a necessary requirement for identifying statistically defensible minimum product time intervals, and in providing confidence intervals for examinations of interannual variability.

3. *Cross-comparison with MSFC/LMA*. Enough LMA stations are now operational to provide lightning location solutions, and a first test dataset was collected in mid-November. Intensive cross-comparison will begin with the spring 2002 season data (an AO response precludes work before then). Again, the complete analysis methodoloy is already a concrete product of this research, so no experiment design stage or 'learning curve' stands in the way of cross-comparison results. The PI rates this as medium priority as the incremental benefit of these analyses over the current work will be to improve sample size and reduce uncertainty; the first order validation results have already been determined as results of 97-MTPE-03 work by our team, Krider et al, and external collaborators.

5. Publications.

Publications and presentations supported or partially supported by this grant, or in which key grant results were presented and used. Relevant results are noted.

Journal publications

Boccippio, D.J., W.J. Koshak, R.J. Blakeslee, 2002a. "Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor: 1. Predicted diurnal variability." *J. Atmos. Oc. Tech.*, accepted with revisions.

Relevant result: LIS and OTD threshold radiance, flash detection efficiency and false alarm rate are predicted (and verified against prior ground validation), along with diurnal variability and intrinsic sensor variability. This yields both calibration corrections and variances for error analysis. This is the primary reference paper for the official released LIS/OTD gridded dataset.

Boccippio, D.J., 2002b. "Lightning scaling relations revisited." *J. Atmos. Sci.*, in press. (also requested as a *Bull. Amer. Met. Soc.* "spotlight" article by the BAMS editor)

Relevant result: The similarity in the spectra of per-cell flash rate distributions over land and ocean is presented (these spectra differ primarily only in frequency of occurrence). This has the implication that spatial variability in the intrinsic variance of the spectrum may be neglected during error analysis, at least for conditionally sampled statistics (storms with flash rates > 1 fl/min).

Boccippio, D.J., K.L. Cummins, H.J. Christian and S.J. Goodman, 2001a. "Combined satellite and surface-based estimation fo the intracloud:cloud-to-ground lightning ratio over the continental United States." *Mon. Wea. Rev.*, **129**, 108-122.

Relevant result: It is demonstrated that the ratio of intracloud (satellite-measured) to cloud-to-ground (ground-measured) lightning over CONUS contains strong spatial variability, that this variability is not explainable by reasonable uncertainty in either platform's calibration, and that this variability is consistent with expected storm physics and prior studies. This provides a "science" validation that the satellite total lightning detectors provide discernible and useful additional information content from intracloud flashes.

Boccippio, D.J., S.J. Goodman and S. Heckman, 2000a. "Regional differences in tropical lightning distributions." *J. Appl. Met.*, **39**, 2231-2248.

Relevant result: The first climatological cross-normalization between OTD and LIS is presented, in the context of a broader science study. Correlation of thunderstorm frequency of occurrence with an environmental parameter is, for the first time, demonstrated.

Williams, E., K. Rothkin, D. Stevenson and D.J. Boccippio, 2000. "Global lightning variations caused by changes in thunderstorm flash rate and by changes in the number of thunderstorms." *J. Appl. Met.*, **39**, 2223-2230.

Relevant result: It is shown that the statistics of per-cell lightning parameters (e.g., cell flash rates) are robust against different implementations of optical pulse-to-flash-to-cell clustering algorithms (i.e., the salient geophysical variability dominates over algorithm nuances). This corroborates the usefulness of the LIS and OTD "area" product algorithms.

Boccippio, D.J., S. Heckman and S.J. Goodman, 2000b. "A diagnostic analysis of the Kennedy Space Center LDAR network. 1. Data characteristics." *J. Geophys. Res.*, **106**, 4769-4786.

Relevant result: An analytic model is built and tested to describe the performance of VHF/Time-Of-Arrival ground based total lightning detection networks, the primary tool for ground-based OTD/LIS validation. The range-dependent sensitivity of these networks was previously unknown. This enables identification of appropriate domains for cross-sensor validation.

Boccippio, D.J., S. Heckman and S.J. Goodman, 2000c. "A diagnostic analysis of the Kennedy Space Center LDAR network. 2. Cross-sensor studies." *J. Geophys. Res.*, **106**, 4787-4796.

Relevant result: The analytic results of part I are tested against LIS and OTD observations. The results are corroborated and a maximum useful range of 90-100 km for the KSC/LDAR network is identified.

Boccippio, D.J., W. Koshak, R. Blakeslee, K. Driscoll, D. Mach, D. Buechler, W. Boeck, H.J. Christian and S.J. Goodman, 2000d. "The Optical Transient Detector (OTD): Instrument characteristics and cross-sensor validation." *J. Atmos. Oc. Tech.*, **17**, 441-458.

Relevant result: The detection efficiency and spatio-temporal location accuracy of the OTD are estimated from ground validation against the National Lightning Detection Network.

Thomas, R.J., P.R. Krehbiel, W. Rison, T. Hamlin, D.J. Boccippio, S.J. Goodman and H.J. Christian, 2000. "Comparison of ground-based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma." *Geophys. Res. Lett.*, **27**, 1703-1706.

Relevant result: The relationship between LIS-observed optical pulses and VHF emissions from growing lightning channels is demonstrated, along with the effects of multiple scattering on detectability of optical pulses originating lower in storms. Location accuracy of the LIS sensor is demonstrated.

Conference presentations

Boccippio, D.J. and H.J. Christian, 2001b. "Application of satellite total lightning observations." 13 July 2001. *8th Scientific Assembly of the International Association of Meteorology and Atmospheric Sciences (IAMAS)*, Innsbrück, Austria (invited talk).

Relevant result: The calibrated, gridded combined dataset was described to the atmospheric chemistry community; issues of data stability, intrinsic measurement variance, sampling bias and the cross-normalization approach were discussed. Long-range (offshore) performance of ground-based systems was presented. "2nd-order" parameters (diurnal cycle phase and amplitude) from the combined climatology were shown.

Koshak, W.J., E.P. Krider and D.J. Boccippio, 2000. "LIS validation at the KSC-ER". *2000 Fall AGU Meeting*.

Relevant result: With consideration of the detailed LIS (x,y,t) sampling volume during KSC overpasses, a LIS nighttime detection efficiency of 92% was demonstrated, validated against both VHF/TOA network observations and ground-based field mill observations. (This is consistent with the 87-97% prediction by Boccippio et al, 2002a).

Boccippio, D.J., W. Boeck, S.J. Goodman, K. Cummins and J. Cramer, 1999. "Intracloud and cloud-to-ground lightning: Comparisons between OTD, NLDN and the GAI long range network." *1999 Fall AGU Meeting*.

Relevant result: An exponential decline in NLDN long range detection efficiency past 1500 km range, at night, was demonstrated by climatological intercomparison with satellite data. (A 10 dB drop in sensitivity during daytime hours, due to lower ionosphere heights, is also shown). This identified a suitable analysis domain for NLDN-based validation of satellite data on a case-by-case (not climatological) basis.

Ushio, T., K.T. Driscoll, S. Heckman and D.J. Boccippio, 1999. "Initial comparison of the Lightning Imaging Sensor (LIS) with Lightning Detection and Ranging (LDAR)." *Proc. 11th International Conference on Atmospheric Electricity (ICAE)*, Guntersville, AL, 738-741.

Relevant result: The vertical distribution of VHF radio sources from lightning channels observed and not observed by the LIS instrument was presented. This provides a basis for expecting differential sensitivity to CG and IC flashes. Similar results were later published in Thomas et al, 2000.

(+ 4 additional papers at the 11th ICAE with content later included in journal papers).

SEMINARS, OTHER.

Boccippio, D.J., 2001d. "LIS/OTD (and TRMM) analysis issues." Invited seminar at the Colorado State University Department of Atmospheric Sciences, 8 June 2001.

Relevant result: LIS/OTD data analysis issues (many overlapping with other TRMM instruments) were presented to the CSU community, many of whom are involved in multisensor TRMM studies. Issues of inferring truth from observation (identifying the instrument response kernel), sampling bias, variance decomposition and adaptive gridding/smoothing were presented.

Boccippio, D.J., 2000e. "Current and future lightning studies at the GHCC: Total lightning detection and applications." 84th Range Commanders Council / Meteorology Group Meeting, 11 April 2000.

Relevant result: Presented VHF/TOA network range-dependent performance estimates and satellite validation results.

Boccippio, D.J., 2000, 2001. "Lightning Imaging Sensor (LIS) validation". Annual progress slides from this grant were included with those submitted by the LIS Science Team and PI (under NRA-99-OES-03) to the TRMM working group.